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Experimental analysis of vortex tube by varying the geometry and material a review

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Review Article

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Abstract

Refrigeration plays an important role in developing countries, primarily for the preservation of food, medicine, and for air conditioning Conventional refrigeration systems are using Freon as refrigerant. As they are the main cause for depleting ozone layer, extensive research work is going on alternate refrigeration systems. Vortex tube (VT) is a non-conventional cooling device, having no moving parts which are capable of separating hot and cold gas stream form an inlet gas stream with a proper pressure without affecting the environment. This device suits for vital applications because of its light weight, simple and more importantly it is compact. This paper presents experimental results by the different investigators on the effect of various geometrical parameters, like nozzles, orifice, conical needle modifications, and different material like metallic and non metallic and experiment, to improve cop, cooling performance of vortex tube under these conditions listed below.

1. *Tangential nozzle orientation with Symmetry/ asymmetry of around 4 nozzles with stopper.*
2. *Cold orifice diameter to the inlet diameter (d/D) and the length to its inlet diameter (L/D)*
3. *Cylindrical and conical hot tubes with conical angle of about 2.5˚ surpassed.*
4. *The effect of varying the cone valve diameter (dc= 14, 12,10,8, and 6mm), with constant nozzle diameter of 6.5 mm by varying the pressure of the inlet air 2-6 bar*
5. *The effects of cooling of a hot tube directly cooled by cooling water jacket.*
6. *The effect of cold end side which has the form of convergent helical nozzles with 7 mm orifice diameter and 6 no. of nozzles by inlet pressure (2 to 5 bar in step of 1bar),conical valves with an angle (30°,45°,60°90°).*
7. *The effect of Ranque-Hilsch vortex tube (RHVT) with threads cut (pitch is 1 and 2 mm) on its inner surface of hot tube.*
8. *Different materials of hot tubes with adiabatic like Mild steel, Aluminium and Copper with same L/D ratio*
9. *By influence of uniform curvature of main tube of VT*

Also by the literature review it is clear that there is no theory so perfect, which gives the satisfactory explanation of the vortex tube phenomenon. Due to this reason researcher conduct the series of experimentation to understand the effect of various parameters mentioned above to improve the performance of vortex tube.

Keywords: Tube, geometrical parameters, orifice diameter, tube length, experimentation, COP, Ranque-Hilsch vortex tube

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1. Introduction

The vortex tube is a thermal static tube that separates compressed gas flow to two streams; one stream colder than the inlet flow while the other stream is hotter than the inlet flow. The vortex tube does not have any moving parts and the separation occurs due to vortex flow generation without requiring any external mechanical work or heat transfer. The vortex tube was first discovered by Ranque **[1],[2]** who was granted a French patent for the device in 1932, and a United States patent in 1934. Ranque encountered the vortex tube phenomenon while he was experimentally working with vortex tube pump in 1928. In 1945, Rudolf Hilsch **[3]**conducted an experiment on vortex tube that focused on the thermal performance with different inlet pressure and different geometrical parameters.

The separation mechanism inside the vortex tube remains until today not completely understood **[4]**. Despite its small capacity, the Ranque-Hilsch vortex tube (RHVT) is very useful for certain thermal management applications because of its simplicity, high durability, compactness, light weight, robustness, reliability, low maintenance cost and safety **[5]**. The RHVT can be classified into two types Eiamsa-ard et al **[6]**: (i) The counter-flow RHVT and (ii) The uni-flow RHVT. In the counter flow RHVT type the cold flow move in the opposite direction with respect to the hot stream, while in the uni-flow type, the hot and cold streams flow in the same direction. In general, the counter-flow RHVT is recommended over the uni-flow RHVT for its efficient energy separation. By Mohammad O et al **[7]** investigates the effect of nozzle's orientation, numbers and symmetric/asymmetric arrangements on the energy separation. Also the study reports COP calculation for the effect of inlet pressure and vortex stopper location. By experimentally Mahyar Kargaran et al **[8]** optimum values for cold orifice diameter to the VT inlet diameter (d/D) and the length of VT to its inlet diameter (L/D) for this experiment proposed. R. Madhu Kumar et al **[9]** were found that the vortex tube with a conical angle of about 2.5˚ surpassed the cylinder tube by 25%~30% in COP. The conical vortex tube reaches the same or more performance than the normal tube but with a smaller length .A study was made by Dr.Ing.Ramzi Raphael **[10]** on the effect of on the performance of uni–flow vortex tube by varying the cone valve diameter (dc= 14, 12,10,8, and 6mm) using two nozzles with varying the pressure of the inlet air within the ranges 2-6 bar. By S. Eiamsa-ard et al **[11]** experiment on the hot tube is directly cooled by cooling water jacket, the mean cold air temperature reduction and cooling efficiency of the RHVT with the cooling of a hot tube are respectively, 5.5 to 8.8% and 4.7 to 9% higher than those of the RHVT without the cooling. Hemant V. Darokar et al **[12]** proposed that different parameters of vortex tube by inlet pressure 2 to 5bar in step of 1bar with conical valves (30°, 45°, 60°, 90°) on the performance study maximum COP and isentropic efficiency found. Jaykumar D. Golhar et al **[13]** observed that experimental results of the energy separation in vortex tubes for different nozzle diameters keeping all other geometrical parameters constant greatly influences the separation performance and cooling efficiency. By Experimentation O.M. Kshirsagar et al **[14]** proposed the effect of various parameters like inlet pressure of air, number of nozzles, cold orifice diameter and hot end valve angle on the performance of vortex tube. Gurol Onal et al **[15]** experimental studied, performance of a tube (RHVT) with threads cut on its inner surface was investigated experimentally (pitch is 1 and 2 mm with inner diameter D=9 and L/D =12. Fraction of cold flow (ξ) = 0.1-0.9, was determined under 300 and 350 k Pa pressurized air. The fabrication and experimental investigation by K. Kiran Kumar Rao et al **[16]** was carried out based on different materials with same L/D ratio of Hot tubes with adiabatic on Mild steel, Aluminium and Copper was used in experimentation. Mohammad Sadegh Valipour et al **[17]** proposed series of experiments has been carried out to investigate the influence of uniform curvature of main tube on the performance of the vortex tube. Mohammad O. Hamdan et al **[18]** proposed that experimental data point out that insulation has minimal effect on the vortex tube performance. The same inlet pressure tests show that energy separation increases as number of inlet nozzle increases **[18].** Gulyaev et al **[19]** recommends a minimum length of 13 times more than that of the diameter. Soni and Thompson **[20]** deduced an L/D greater than 45 for efficient working. Singh P.K and et al **[21]** states that the effect of nozzle design is more important than the cold orifice design in getting higher temperature drops. Balmer et al **[22]** has demonstrated that the heat separation, which occurs inside the Ranque–Hilsch a vortex tube is not limited to compressible gases and can be applied for non compressible fluids as well. Dincer et al**. [23]** investigated the effect of control valve tip angle on performance of Ranque-Hilsch vortex tube using different inlet pressures. Behera et al**. [24]** showed from solutions obtained using computational fluid dynamics that this secondary flow could be related to the cold end cross-sectional area. It was concluded that a secondary flow would occur when the cold end cross-sectional area was small. Dincer et al **[25]** carried out energy analysis of the vortex tube with regard to nozzle cross sectional area and suggested that the variation of the energy efficiency increased with increasing pressure and cold fraction.

Kun Chang et.al **[26]** performed experimentation with hot divergent tube and found that the Energy separation performance of vortex tube can be improved by using a divergent hot tube. Rahim Shamsoddini et.al **[27]** observed on Effect of number of nozzles on the flow and power of cooling of a vortex tube using a three-dimensional numerical fluid dynamic model. It is observed that as the number of nozzles is increased, power of cooling increases significantly while cold outlet temperature decreases moderately. Nimbalkar et al **[28]** and Muller presented the results of a series of experiments focusing on various geometries of the ''cold end side" for different inlet pressures and cold fractions. K. Kiran Kumar Rao1 et al [29] presented the results by using homogenous wood like rose wood and sapota wood with Length of the Hot pipe = 290mm Diameter of the hot Pipe = 12mm with L/D ratio=24.

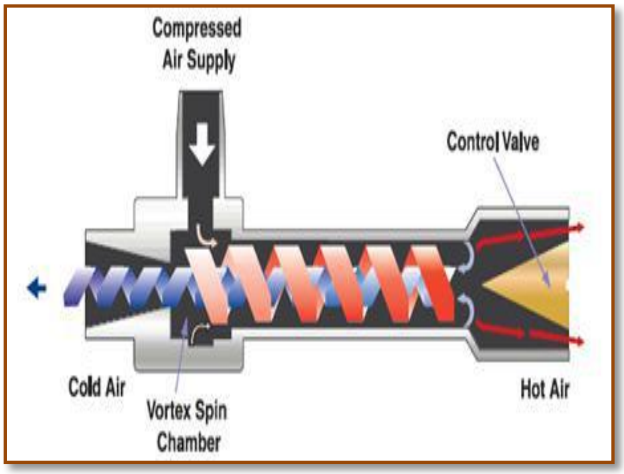


Fig. 1 Vortex tube schematic

1.1. Types of vortex tubes

There are two classifications of the vortex tube [6]. Both of these are currently in use in the industry. The more popular is the counter-flow vortex tube (Figure 2). The hot air that exits from the far side of the tube is controlled by the cone valve. The cold air exits through an orifice next to the inlet. On the other hand, the uni-flow vortex tube does not have its cold air orifice next to the inlet (Figure 3). Instead, the cold air comes out through a concentrically located annular exit in the cold valve. This type of vortex tube is used in applications where space and equipment cost are of high importance. The mechanism for the uni-flow tube is similar to the counter-flow tube. A radial temperature separation is still induced inside, but the efficiency of the uni-flow tube is generally less than that of the counter-flow tube.

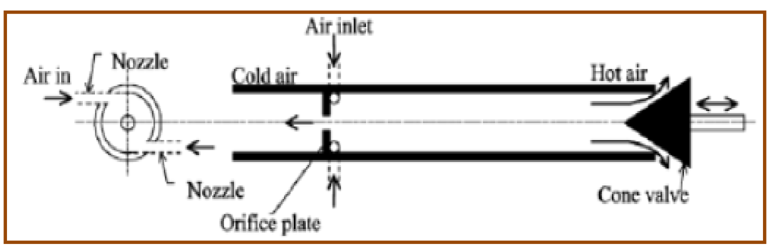


Fig. 2 Counter-flow vortex tube

2. Experimental setup:

By Mohammad O.et al [7] investigates the effect of nozzle's orientation, numbers and symmetric/asymmetric arrangements on the energy separation. Also the study reports COP calculation for the effect of inlet pressure and vortex stopper location. A two-dimensional cross section of used vortex tube is shown in Fig. 4a. Room temperature compressed air is used as working fluid at different inlet pressure values. The compressed air enters in the middle of the vortex tube to a chamber that distributes the air into multiple inlet nozzles that promote vortex flow generation within the vortex generator, Fig. 4b. The vortex flow get separated to two outlets where hot air leaves from the outer perimeter of the vortex while cold air leaves from the centre of vortex at the opposite direction as shown in Fig.4a. A vortex stopper shown in Fig. 4c is used to stop the flow from rotating while leaving the hot side of the vortex tube.

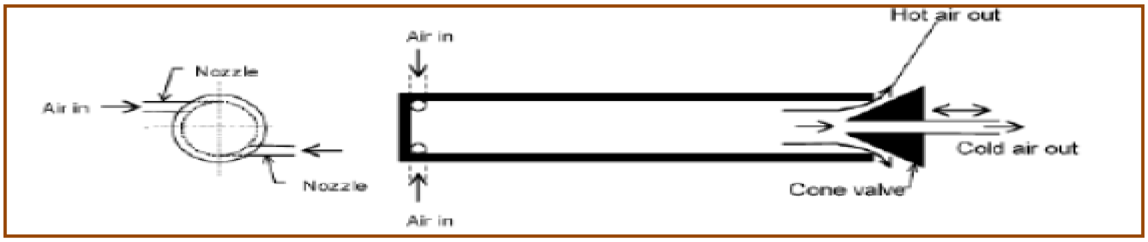
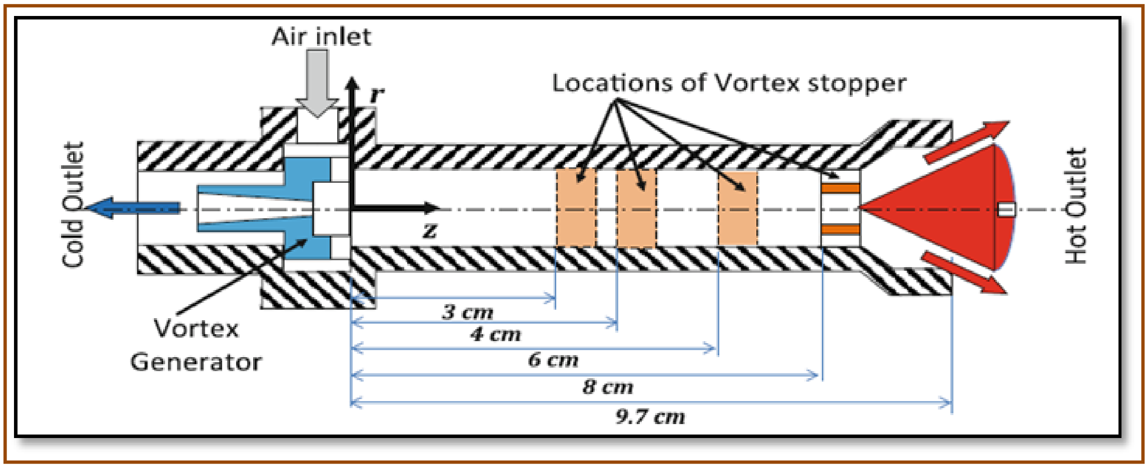
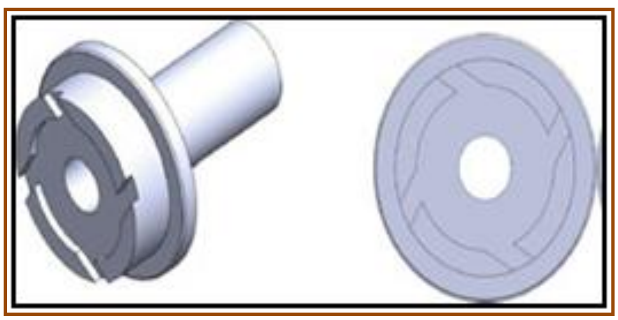


Fig. 3.Uni-flow vortex tube



a)



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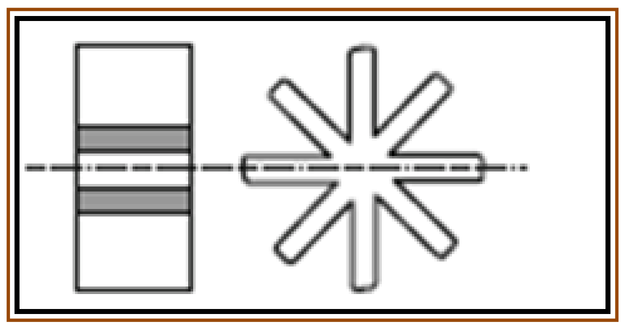

c)

Fig 4 a).Vortex tube cross section, b) Vortex generator c) Vortex stopper

The compressor maximum rated pressure is 12 bars, storage tank size is 1 m3 and the compressed air is expanded in the vortex tube chamber and separated into hot air stream and cold air stream. The cold stream in the central region flows out of the tube through the central orifice nearer to the inlet nozzle, while the hot stream in the outer annulus leaves the tube through other outlet far from the inlet. The temperatures of the inlet and outlet flows are measured with multiple thermocouples to assure better average temperature measurements. In the present study, the vortex tube is made of stainless steel with inner diameter of 10 mm. The whole length of the tube is137 mm. The outlet diameter of the cold side is 4.5 mm and hot side end is around 8 mm. The inlet flow rate is controlled through the flow meter valve which implicitly determines the inlet pressure. The temperature is measured using type- K thermocouple with uncertainty of 0.30C. In this experiment, different inlet pressure sets were used in the test ranging from 2 to 5 bars at room inlet temperature. The volumetric flow rate of the inlet stream is measured by a glass flow rotameters with uncertainty of 0.5 L/min (2.9 9 10-3 kg/min at 5 bar). The cold outlet flow stream is measured using one of two glass flow rotameters with uncertainty of 0.5 L/min (5.8 9 10-4 kg/min at 1 bar) and 0.05 L/min (5.8 9 10-5 kg/min at 1 bar), respectively. The low accuracy of 0.5 L/min (5.8 9 10-4 kg/min at 1 bar) rotameter is used when high cold flow rate is expected which occurs when the hot side is nearly closed. The high accuracy of 0.05 L/min (5.8 9 10-5 kg/min at 1 bar) rotameter is used when low cold flow rate is expected which occurs when the hot side is nearly fully open. The temperatures of the inlet and outlet flows are measured with multiple thermocouples.

All experimental runs are conducted in similar manner following a specific procedure, where the compressor runs for half hour to allow reaching steady state temperature of inlet compressed air. The pressure inside the pressurized tank is kept higher than 6 bar while a check valve is used to assure continuous uniform inlet pressure of 5 bars to the experiment. Incase pressure drop inside the tank below 6 bars the test is hold till pressure is build up inside the air tank. A short plastic pipe connection is used at the cold/hot outlet to allow fixing the thermocouples and to reduce the effect of heat transfer. The temperatures are logged in over a period of time using portable handheld data logger with eight data inputs. A Borden tube pressure gage with 0.2 bar uncertainty is used to measure the inlet pressure.

Mahyar Kargaran et al [8] proposed that to achieve the maximum proficiency of a vortex tube, form the data which obtained experimentally, optimum values for cold orifice diameter to the VT inlet diameter (d / D) and the length of VT to its inlet diameter (L/ D) for this experiment proposed. d / D = 8 / 25 =.32 and Lh/D =769 / 25 = 30.76. As far as cooling capacity and hot temperature difference are concerned, the study indicates that the aforementioned ratios are same for them .It means that for orifice d=8mm and hot tube length Lh=769 mm we can reach the maximum proficiency of a vortex tube for the current study. As for μC value, at μC ≈ .6 we witness the maximum of cold temperature difference and cooling capacity, while for hot temperature difference μC is about .75.

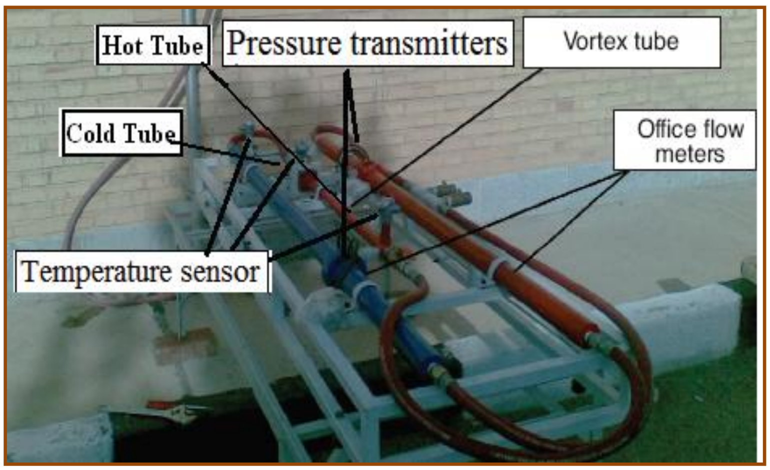

Fig 5 The experimental test bed in operation

Figure 5.shows the experimental test bed has been conducted at Koolab Toos Company to investigate thermal separation of air as working fluid. The inlet pressure was varied during experiments from 4.2 to 5.8 bars which are gauge pressure and the inlet temperature was 25.4°C.Noting from the figure, the hot length of the VT and hot stream flow meter were painted in red. In other hand, the cold length of the VT and cold stream flow meters were painted in blue. The VT was made from steel with inlet diameter of 25 mm. During the tests, the hot tube length of the VT was varied among 3 available as detailed.

Dr.Ing.Ramzi Raphael Ibraheem Barwari et al [20] proposed that by varying the cone valve diameter (dc= 14,12,10,8, and 6mm) on vortex tube using two nozzles with constant nozzle diameter (dn = 6.5 mm) and varying the pressure of the inlet air (Piabs) as well as cold air mass ratio(Y) within the ranges (Piabs = 2-6 bar)and (Y =0 – 1)consecutively . The experiments showed an optimum design of uni-flow vortex tube that gave high energy separation at cone valve diameter (dc= 12mm) for four vortex-tube diameters (D=30, 20, 15mm and taper). As for the vortex tube with (D = 10 mm), the cone valve diameter that gave high energy separation was (dc= 8 mm) with a number of nozzles (N = 2).

S. Eiamsa-ard et al [23] proposed that the effects of cooling of a hot tube on the temperature separation (the temperature reduction of cold air and cooling efficiency in a counter-flow Ranque–Hilsch vortex tube (RHVT). In the experiments, the hot tube is directly cooled by cooling water jacket. The obtained results reveal that cooling water plays an important role in promoting the energy separation in the RHVT. Consequently, the temperature reduction of the cold tube (Ti−Tc) and thus cooling efficiency in the RHVT with cooling of a hot tube is found to be higher than those of the RHVT without the cooling, under the similar operating conditions. Over the range investigated, the mean cold air temperature reduction and cooling efficiency of the RHVT with the cooling of a hot tube are respectively, 5.5 to 8.8% and 4.7 to 9% higher than those of the RHVT without the cooling. Details of the counter-flow RHVT are displayed in Fig. 6. As shown, the counter-flow RHVT consists of the cold/hot tube, cold orifice plate, vortex chamber with snail entry and control/cone valve. The cold tube was made of acrylic with 16 mm in diameter. At lower cold mass fraction, unreleased cold air moves to mix with hot gas at the outer region. In contrast, at higher cold mass fraction, unwanted hot air is released with cold air through the cold gas orifice. For the present range studied, the RHVTs with 1, 2, 3 and 4 inlet nozzle(s), yield the maximum cold temperature reductions and cooling efficiencies of about 18.7 °C, 19.8 °C, 20.3 °C and 21.8 °C; and 23.5%, 24.9%, 25.5% and 27.4% for μc=0.3, 0.34, 0.29 and 0.33, respectively.

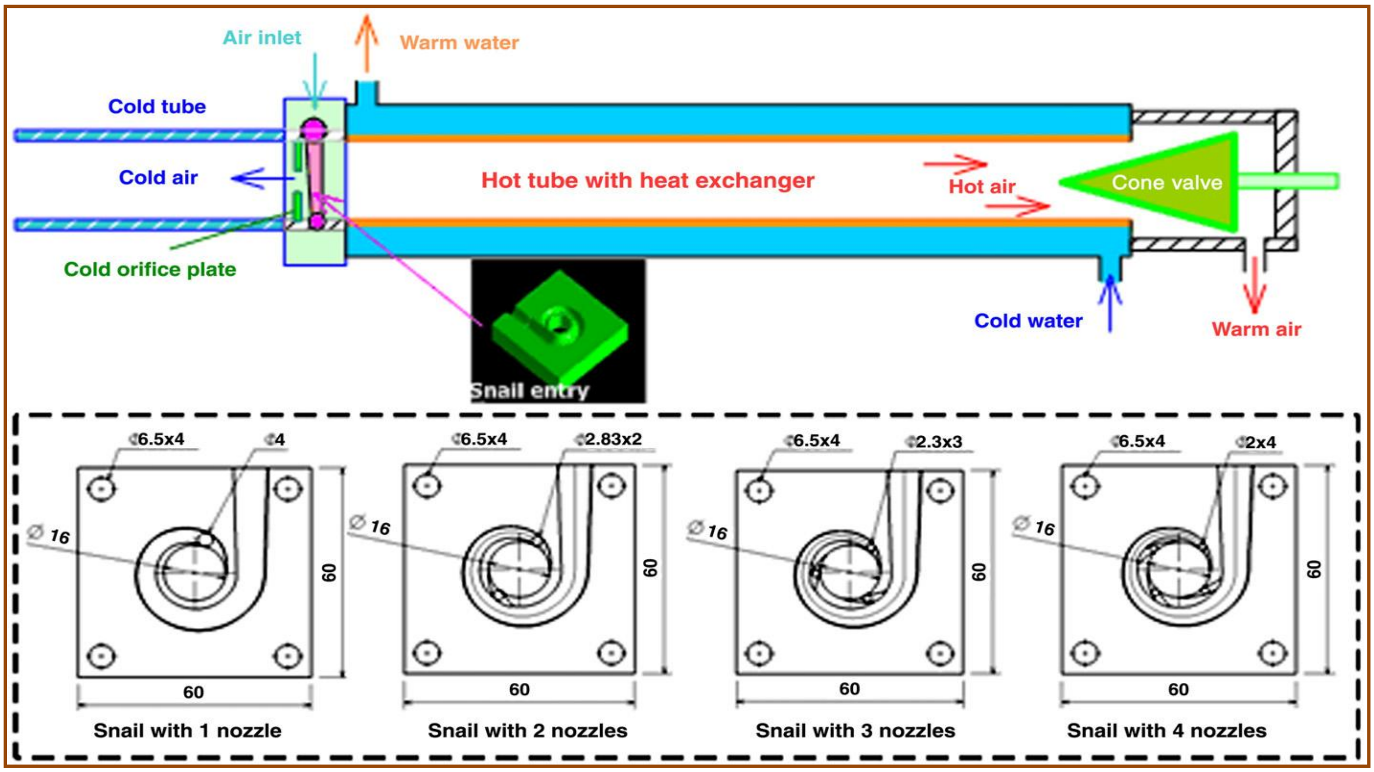

Fig. 6 Counter-flow RHVT with cooling surface of hot tube

Hemant V. Darokar et al **[17]** proposed a new geometry for cold end side which has the form of convergent helical nozzles in the figure 7.is shown as 8mm to 3mm, divergence angle 60 hot tube with 225mm length and diameter 12.5mm. Cold ends are manufactured with 7 mm orifice diameter and 6 no. of nozzles. The effect of inlet pressure (2 to 5bar in step of 1bar, conical valves in figure 8. (30°, 45°, 60°, 90°) on the performance of` vortex tube is analyzed. At the end of study maximum COP and isentropic efficiency found to be 0.376 and 23% for 45° conical valve at 5 bar pressure.

Jaykumar D. Golhar et al. **[13]** proposed in his investigation simple counter-flow vortex tube consists of a long hollow cylinder with tangential nozzle at one end for injecting compressed air. Compressed air supplied to the vortex tube is separated into low pressure hot and cold air from its two ends. The exact mechanism of this temperature separation is not known today. Most of the investigators have studied the various operating characteristics of vortex tube based on the cold air fraction. Vortex tubes of different geometrical configurations give optimum performance at different cold fractions.

This paper presents experimental results of the energy separation in vortex tubes for different nozzle diameters keeping all other geometrical parameters constant. It is experimentally evidenced that the nozzle diameter greatly influences the separation performance and cooling efficiency. The most important point revealed in this paper is that there is an optimum nozzle diameter that gives the best performance of vortex tube. The schematic of the experimental apparatus and measuring devices which is used for the determination of the energy separation in a vortex tube is shown in figure 9.

Fig. 7. Inlet cap (cold end) and Geometry for convergent nozzle

Fig. 8 Conical valve used for experimentation

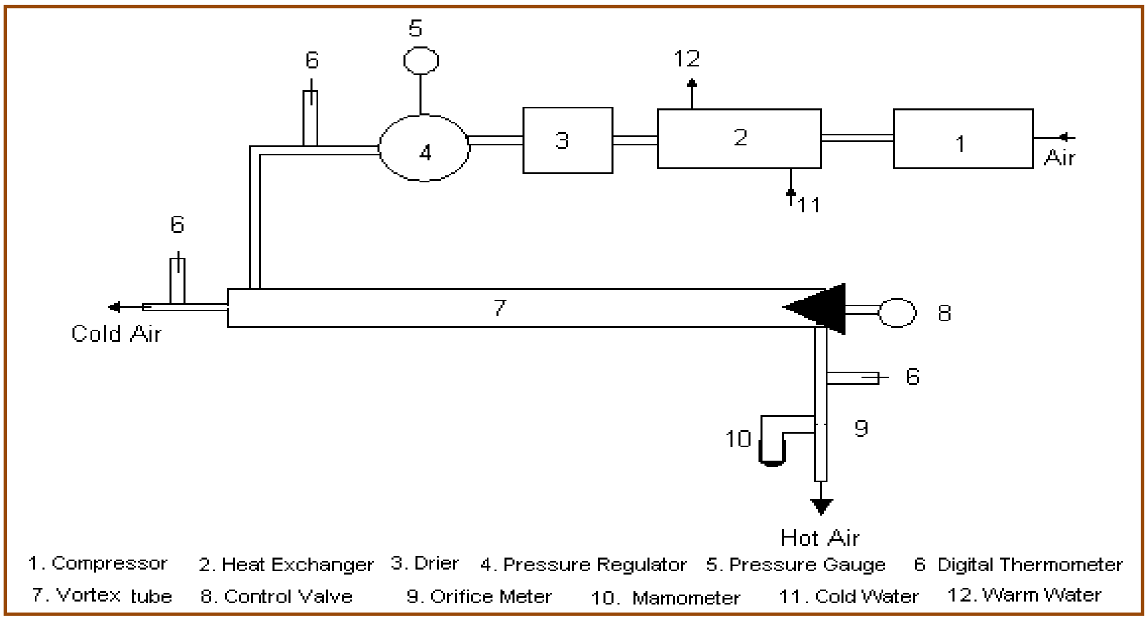

Fig. 9. Schematic diagram of the experimental apparatus and measuring devices

Compressed air is passing through the heat exchanger (2) and drier (3). Pressure regulator (4) is used for controlling the pressure of inlet air. Since then it is injected tangentially into the vortex tube (7). The compressed air expands in the vortex tube and meanwhile it is divided into cold and hot streams. The cold air leaves the central orifice near the entrance nozzle, while the hot air discharges the periphery at the far end of the tube. The control valve (8) controls the flow rate of the hot air. The mass flow rates at the hot outlet of the counter flow Ranque–Hilsch vortex tubes can be calculated by standard calibrated orifice meter (9) and manometer (10) fitted to hot exhausts. The inlet temperature, the hot outlet temperature and the cold outlet temperatures of the counter flow Ranque–Hilsch vortex tube have been measured by use of digital thermometers (6). The pressure of inlet gas is measured by pressure gauge (5).

O. M. Kshirsagar et al [14] proposed in his experimentation of this paper is to understand the effect of various parameters like inlet pressure of air, number of nozzles, cold orifice diameter and hot end valve angle as shown in Figure.10, Figure 11.on the performance of vortex tube. Also by the literature review it is clear that there is no theory so perfect, which gives the satisfactory explanation of the vortex tube phenomenon. Due to this reason researcher conduct the series of experimentation to understand the effect of various parameters mentioned above on the performance of vortex tube.

i. Effect of cold orifice diameter on performance of vortex tube:

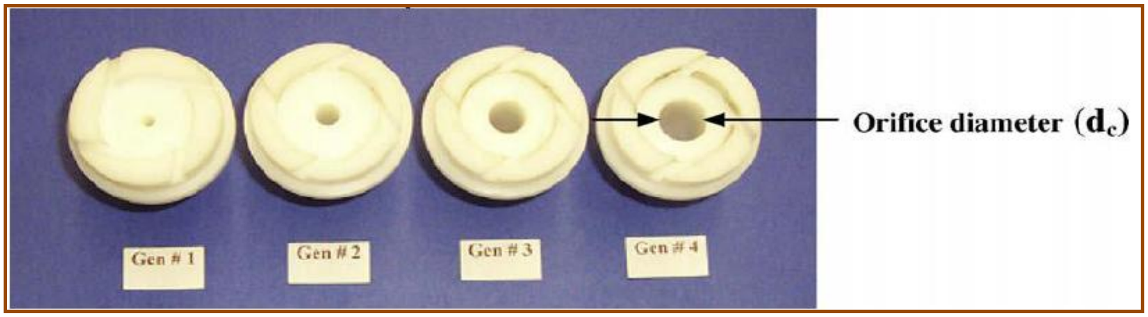

Fig. 10 Lab manufactured generators with varying orifice diameter.

ii. Effect of number of nozzle used:

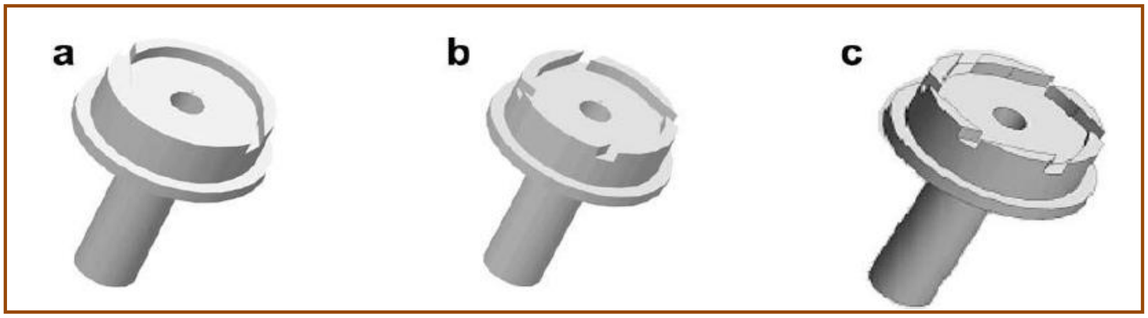

Fig. 11 Nozzles used in experiments: (a) 2 nozzle, (b) 4 nozzle, and (c) 6 nozzle

Figure 10.shows the effect of 2, 4, and 6 nozzles on the performance of the vortex tube, when the operating pressure is increased. An increase in the pressure at the entrance of the vortex tube results in an increase in the performance of the vortex tube with 2, 4, 6 nozzles. The best performance is obtained with the vortex tube which has 4 nozzles.

iii. Effect of hot end valve angle on performance of vortex tube: the effects of angle at the tip of the plug for 30°, 60°, 90°, 120°, 150° and 180° on the performance of the vortex tube. When the experimental data are assessed, it is found that the biggest ΔT values are observed with the plug which has a tip angle of 30° or 60°.

Iv. Effect of inlet air pressure on performance of vortex tube: The variation in the temperature difference with different values of inlet air pressure and cold air mass fraction. The pressure at the entrance of the vortex tube was increased from 200 k Pa to 420 k Pa by increments of 20 k Pa. Hence effect of the inlet pressure of the vortex tube on the tube's performance was experimentally examined, it can be seen that the ΔT constantly increases from 200 k Pa to 380 k Pa, but the increase is less significant between 380 k Pa and 420 k Pa for the geometry and dimensions of the vortex tube employed.

Gurol Onal et al **[15]** has presented in this experimental study, performance of a counter flow RHVT The inner diameter of the vortex tube used was D=9 mm and the ratio of the tube's length to diameter was L/D=12. The experimental system was a thermodynamic open system. Flow was controlled by a valve on the hot outlet side, where the valve was changed from a nearly closed position to its nearly open position. Fraction of cold flow (ξ) = 0.1-0.9, was determined under 300 and 350 K Pa pressurized air. All with threads cut on its inner surface was investigated experimentally.

K. Kiran Kumar Rao et al **[16]** proposed that based on different materials of hot tubes like Mild steel, Aluminium and Copper used in fabrication by that the maximum hot air temperature and minimum cold air temperature were found. The fabrication and experimental investigation was carried out based on by using same L/D ratio 22 /8 with adiabatic process of Hot tube, nozzle 8 mm diameter and orifice 6 mm diameter used .Figure 11. Shows the parts of vortex tube. Figure12. shows the adiabatic process of hot tubes.

Fig.12 .Parts of vortex tube

Fig. 13. Hot tubes

Mohammad Sadegh Valipour et al **[17]** investigate the influence of uniform curvature of main tube on the performance of the vortex tube show that the curvature in the main tube has different effects on the performance of the vortex tube depending on inlet pressure and cold mass ratio. In this paper a series of experiments has been carried out to investigate the influence of uniform curvature of main tube on the performance of the vortex tube. The main tube is made of copper with different turning angle and curvature radius for all vortex tubes, however the axial curvature is uniform (see Fig.14). Fore each tube, Inner surface is perfectly smooth and their inner diameters are kept completely constant. Length (L) and inside diameter (D) of main tubes are the same for all three vortex tubes; however their curvature radiuses and their turning angles are different as indicated in Table 1. The diameter of cold flow orifice is selected like dc ¼ 0.5D, this has been proposed as optimum diameter (Saidiand Valipour, 2003), and it is similar among all three vortex tubes. A conical valve which is also similar in all three vortex tubes is used for hot flow regulation as demonstrate. Top event heat losses and to reach reliable results, outer body of vortex tubes and all Connecting pipes have been isolated in this set up.

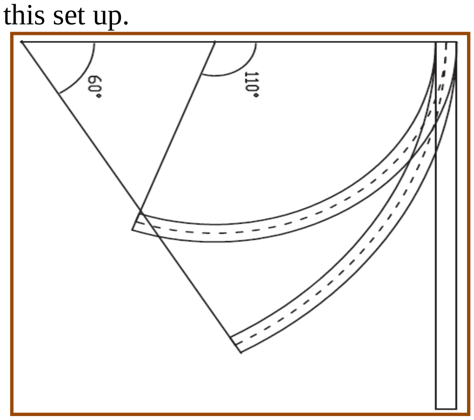

Fig. 14 Geometries of the main pipe (curved and straight)

K. Kiran Kumar Rao1 et al **[29]** to study the effect of geometrical parameters on vortex tube made of two types of homogeneous wood to check the performance by using compressed air as a working fluid .The data was presented till date of the experimental work carried out by researchers for optimum performance of a vortex tube made of Rose wood and Sapota wood parameters such as the length of VT to its inlet diameter (L/ D) ratio as 24, use of different material in developing the vortex tube and its effect are discussed in detail. As shown in figures 15, 16

Fig. 15 Hot tubes made of rose wood

Fig.16 Hot tubes made of sapota wood

3.2. Applications of Vortex Tube:

- Simple in constructions
- No moving parts,
- No chemicals
- Light weight
- Low cost
- Maintenance free
- Instant cold air
- Durable for its application
- Therefore, if compactness, reliability and lower equipment
- Cost is the main factors, the vortex tube recommended for spot cooling
- Now lot of research works is going on the vortex tube to improve its performance

3.2. Applications of Vortex Tube

- Vortex Tube Based Refrigeration
- A Vortex Tube For Carbon Dioxide Separations
- Personal Air Conditioning
- Cutting Tools
- Shrink Fitting
- Cooling Of Gas Turbine Rotor Blades
- Laboratory Sample Cooler
- Cooling Of Machine
- Cooling Electrical Cabinets
- Cooling Mould Tools
- Cooling Sewing Needles
- Cooling Of Hot Operations
- Cooling Workers
- Testing Thermostats Cooling CCTV Cameras
- Setting Hot Glue Operations
- Cool Soldering
- Air Suits

4. Conclusion:

The following conclusion has been drawn from the experimentation:

1. It is clear to that always the performance of vortex tube is directly proportional to inlet compressed air.
2. The cold mass fraction is an important parameter influencing the performance of the energy separation in the vortex tube
3. The effect of number of nozzle is very important for improve better cop.
4. The secondary circulation zone is determined by controlling the vortex stopper location.
5. The nozzles symmetry or asymmetry has insignificant effect on the vortex tube performance.
6. VT inlet diameter (d / D) and the length of VT to its inlet diameter (L_h /D) for influencing the cop.
7. The surface finish of the nozzle and the hot tube plays a great role in the performance of the vortex tube , good surface finish leads to the better performance so care to be taken while fabrication of the parts to obtain to get good surface finish.
8. Geometry for cold conical valves is improving at 45° valve and 90° a best result.
9. The effect of the conical hot tube also influencing on cop
10. With the cooling of a hot tube are respectively, 5.5 to 8.8% and 4.7 to 9% higher than those of RHVT without the cooling (insulation only).

11. Depending up on materials (Thermal conductivity) also different in cop of VT. It is clear that no difference in cop with or without adiabatic (hot tube).
12. From the experimentation it is found that the biggest ΔT values are observed with the plug which has a tip angle of 30° or 60°.
13. It was determined that Fraction of cold flow (ξ) = 0.1-0.9, at L/D=12 at pitch=1 mm, 350 k Pa the maximum heating performance of the RHVT was 38.2^{o} C and the maximum cooling performance was -30.9^{o} C.

5. Future Scope

As we all know there are no limits for improvements in any kind of work or we can say nothing is best. There is always scope for improvements in present work. So, Vortex tube is not an exception. Several investigators have modified the in geometric design of present vortex tube and tested for better performance. But there are still so many options available on which experiments can be done. After some experimental analysis work studied which is done by various researchers, on geometrical modifications for improving the performance of vortex tube are as listed below:

i. We can increase number of inlet air entries.
ii. Guiding element inside the Vortex tube can be provided for guiding inlet air circumferentially towards hot end.
iii. Experiments are also possible with varying the length of Cold ends and Hot ends.
iv. Same Vortex tube as we have manufactured can be tested by using water as cooling agent.
v. We can try some modification in the geometry of convergent nozzle with the help of CFD analysis.
vi. We can try the same geometry in different material and compare it to find the dependency on material of the vortex tube.
vii. We can try the non metallic materials like homogeneous wood, Acrylic, Nylon, PVC, CPCV etc,
viii. We can try different types of fluids like carbon dioxide, hydrogen as inlet element.
ix. We can try different types spiral type of hot tubes with different types of material for better analysis

Nomenclature

COP	*Coefficient of performance*
Cp	*Specific heat constant (kJ/kg K)*
D	*Vortex tube inner diameter (m)*
L/D	*Length/inner diameter of vortex tube*
P_{in}	*Inlet pressure (bar)*
m_h	*Hot mass flow rate (kg/s)*
m_c	*Cold mass flow rate (kg/s)*
m_{in}	*Inlet mass flow rate (kg/s)*
RHVT	*Ranque-Hilsch Vortex tube*
r	*Radial coordinate*
T_h	*Hot outlet temperature* (^0C)
T_c	*Cold outlet temperature* (^0C)
T_{in}	*Inlet temperature* (^0C)
(L_h)	*Hot tube length*
(L_c)	*Cold tube length*
(*d*)	*Cold orifice diameter*
(δ)	*Inlet nozzle diameter*
(ϕ)	*Conical controlling valve angle*
μ_C	*Ccold mass fraction*
q_c	*Specific cooling capacity*
D_N	*Diameter of nozzle*
d_c	*Cone valve diameter*
P_{iabs}	*Pressure of the inlet air*
Y	*Cold mass fraction*
M	*Mass flow rate, kg/s*
P	*Pressure, bar*
T	*Temperature, K*
μ_c	*Cold mass fraction*
η	*Cooling efficiency*
γ	*Specific heat ratio*
ΔTc_{max}	*Maximum temperature drop*
D_n	*Nozzle dia*
Φ	*Nozzle angle*
D_o	*Orifice diameter*
ξ	*Fraction of cold flow*
α	*Tturning angle of main tube (dimensionless)*
R	*Radius of curvature (m)*
κ	*L/R*
$\dot{m}$	*Mass flow rate* ($kg\ s^{-1}$)
$\tilde{V}$	*Volume flow rate* ($m^3\ s^{-1}$)
R_{air}	*Gas constant of air* ($kJ\ kg^{-1}\ K^{-1}$)

Subscript

a	*atmosphere*
is	*isentropic process*
i	*inlet*

Q_r	*Refrigeration capacity*	*c*	*cold flow*
		h	*hot flow*

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